LABORATORY DEVELOPMENTS FOR STUDY OF FLOW IN ROTATING CHANNELS.

by R.T. Knapp[1], A. Hollander[2], A.J. Acosta[3], and W.C. Osborne[3]

- to be presented at the Annual Meeting of the
American Society of Mechanical Engineers
November 28-Dec. 3, 1948 -

I. Laboratory Background

The Hydrodynamics Laboratories of the California Institute of Technology are a group of closely associated laboratories operating as a unit. They include the Hydraulic Machinery Laboratory, the Hydrodynamics Laboratory, the Sedimentation Laboratory, and the Hydraulic Structures Division, which has laboratory facilities both on the campus and at Azusa, 15 miles to the east. The Hydraulic Machinery Laboratory and the Hydrodynamics Laboratory are housed in adjoining sections of the same building on the campus. The basic equipment of these two laboratories has been described in previous articles in the Transactions.[4](1,2).

The Hydraulic Machinery Laboratory was designed primarily for the study of the performance characteristics of complete hydraulic machines. For example, this laboratory was used to study the pumping problems of both the Metropolitan Water District of Southern California and the Grand Coulee Project of the Bureau of Reclamation, and also to carry out precision tests of the preliminary and final models of the pumps accepted for installation on both projects. Both of these programs,(13 to 16) involving

---

[1]Director, Hydrodynamics Laboratories, California Institute of Technology, Pasadena, Calif. Mem. ASME.

[2]Research Engineer, Hydrodynamics Laboratory, California Institute of Technology, Mem. ASME.

[3]Mechanical Engineer, Hydrodynamics Laboratory, California Institute of Technology.

[4]Numbers in parenthesis refer to bibliography at end of paper.

very extensive studies of the complete machines, served to emphasize the need for much more basic knowledge in the entire field of rotating hydrodynamic machinery. The Hydrodynamics Laboratory staff gave much thought to the consideration of the type of program that would most effectively meet this need. It was concluded that while the original Hydraulic Machinery Laboratory could be used to good advantage, the equipment was inherently larger in size and in power consumption than was necessary or desirable for much of the work. It was felt that smaller equipment with correspondingly lower power could carry out such a program much more effectively and economically. Furthermore, if such equipment were built for the particular purpose of making such fundamental studies, it could be designed to utilize newly developed experimental techniques which would be difficult, if not impossible, to employ in the original laboratory without very extensive modifications.

II. Initiation of Project

In line with these conclusions, the plans for a basic research project for the study of flow in rotating channels were prepared by the laboratory staff and submitted to the Office of Naval Research of the U. S. Navy for their consideration and possible support. After careful study, the ONR agreed that the objectives of this proposal were in line with their general nationwide effort to broaden the knowledge of theoretical and practical hydrodynamics in all fields of interest to the Navy. The result was that in January 1947 a contract was made between the Office of Naval Research and the California Institute of Technology for the support of the program. This project, designated as NR 062-010, forms a part of the research program sponsored by the Fluid Mechanics Branch of the ONR. The purpose of this article is to discuss some of the general objectives of the program, to give a brief outline of the design, construction, and installation of the necessary additions to the laboratory equipment, and to present a glimpse of a few details of the first investigations.

III. General Objectives

In the past most of the experimental work carried on in the field of rotating machinery has dealt with the machine as a whole, and because of the technical difficulties involved, comparatively little has been done to determine the performance characteristics of the individual elements which make up the whole. As a rough classification, such a machine can be thought of as consisting of three parts: (a) the stationary inlet member, (b) the rotating member, and (c) the outlet stationary member. The stationary members, particularly in pumping units, are often called the case. Some empirical work has been carried out in which various rotating members have been tested with the same stationary members and vice versa, but the test results obtained in these cases have been referred to the performance of the combination as a complete machine, and the effect of changes in the individual member has been inferred only through the effect of such changes on the over-all performance. Several laboratories, particularly those of Spannhake, Thoma, and Pfleiderer in Germany (3 to 11) have undertaken experimental investigations of the detailed characteristics of the flow in the rotating passages and a few workers have explored the flow during its transition from the rotating member to the case. In practically all instances, however, the experimental machine has been greatly simplified, usually to the point of making the runner two-dimensional. The gain from such simplification has been twofold: the experimental difficulties have been lessened appreciably, and the possibility of parallel analytical studies has been improved. Unfortunately, the losses accompanying the simplification have included large decreases in efficiency, lowered resistance to cavitation, and a general lack of similarity to the performance characteristics of modern hydraulic machines. Much effort has been devoted to the development of a satisfactory analytical treatment of the flow in hydraulic machines. Considerable progress has been made in the analysis of the axial flow machine, especially in the zone of efficient operation. However, for abnormal operating conditions even in the axial flow machines, and for all conditions in the machines having appreciable components of radial flow, the present analytical methods leave much to be desired.

If the performance of the individual elements of machines having good characteristics and high efficiencies could be obtained experimentally, and especially if the details of the flow could be determined, as well as the over-all characteristics of the elements, it would greatly enlarge the possibilities of developing a satisfactory analytical treatment and at the same time improve design possibilities through the use of more detailed empirical information. Therefore, it was decided that one of the primary objectives of the present program would be the investigation of each individual component of the rotating machine. Furthermore, it was felt that the rotating member should be the first component studied. The reason for this choice is that the rotating member is the primary component of the machine, since the interchange of energy between the machine and the fluid takes place in the rotating passages. The equipment described in the following section was designed as a necessary step in the attainment of this objective, starting with the study of the flow in the rotating member.

In planning the program and designing the equipment, several additional considerations have been kept in mind. For example, rotating hydraulic machines have two primary functions: to develop mechanical energy by removing energy from the fluid flowing through the machine, or to add energy to the fluid by supplying mechanical energy to the machine. Turbines perform the first function, pumps and compressors the second. Often the same machine can perform either function with high efficiency, the change in function being accomplished by reversing the directions of flow and rotation. Obviously, both functions must be investigated, with much attention to the clarification of their points of similarity and the emphasis of their points of difference. Another consideration is that the experimental program and equipment should be planned to take advantage of all of the modern experimental tools for studying flow. One of the most powerful of these is the high speed motion picture, which can be used to obtain quantitative measurements of flow patterns. This technique requires the use of transparent machine elements; hence, the plans for plastic or glass members. The use of high speed motion pictures has another advantage since it has proved to be such an effective tool for the study of cavitation (12), and the cavitation characteristics are one of the most important characteristics of an hydraulic machine. However, an experimental study of cavitation has little meaning unless it is possible to control accurately the shapes and surfaces of the fluid passages. Thus the planning of the program must include the development of suitable precision methods of construction of the experimental machine elements.

It is realized that a misunderstanding might easily arise concerning the proposal to study the characteristics of the individual members of the machine. There is no intention to imply that the performance of each element does not affect that of all of the others, or that it is possible to isolate each in turn and study it alone. Obviously, the same fluid passes through all parts of the machine. Therefore, for example, the investigation of the flow in the rotating passages cannot be completed without the study of the effect of varying inlet and outlet conditions. Thus the program contemplates that when the pumping function of the rotating passage is being explored, it will be necessary to include the determination of the effect of inlet guide vanes and other methods of flow control. Likewise, the performance of the outlet stationary member undoubtedly will be affected by the type of velocity distribution which results from the flow through the rotating member. This simply means that it will often be necessary to incorporate two or all three of the machine members into the test set-up even though the actual measurements are confined to one member only. Such a set of objectives and considerations point to the need of extreme flexibility and versatility in the test set-up. The following description of the equipment and instrumentation will show how these demands have been met.

IV. Description of Equipment

The General Circuit

The Rotating Channel Project shown in Fig. 1 is located on the mezzanine floor of the Hydraulic Machinery Laboratory. It provides a flow of water in a closed circuit which is shown schematically in Fig. 2, and which may be considered as consisting essentially of three principal sections. One section functions primarily as a supply reservoir and includes the necessary equipment to deliver and meter a steady flow of water at various pressures and flow rates. It includes the reservoir and supply pump, the venturi meters and the throttle valve. This part of the circuit of which the supply pump motor and venturi motor are partially visible in Fig. 1 along the west wall and which is shown in detail in Fig. 3, is independent of whatever test arrangement is made, and thus little change should be required in its composition and arrangement. It is constructed of standard weight, 8 in. galvanized pipe and fittings and is secured rigidly to the laboratory structure.

The second section functions principally as a distribution circuit and includes a flexible array of distributing headers, valves and piping shown in Figs. 4 and 5, which may be arranged in various combinations to carry the flow from the throttle valve to and from the test elements in the particular manner and direction required by the unit under observation. Fig. 2 shows two of the several flow circuits possible. The major portion of this section is considered expendable since, although the arrangement is adequate for the research foreseen at this time, it is entirely possible, that as the work progresses, minor and even major changes may be required. Most of this part of the circuit is made up from 10 in., 12 gage galvanized spiral pipe, and is relatively independent of the laboratory structure.

The test stand shown in the center foreground in Fig. 1 constitutes the third part of the circuit. Here are included facilities for mounting, operating, and testing hydraulic machine elements. The principal parts are the approach piping, the test basin, and the vertical dynamometer. These components are all in duplicate and thus allow two different studies to be run alternately, that is one test set up can be installed or worked upon while experiments are carried on with the other.

The project is a self-contained unit and can be operated independently of the other equipment in the building. However, to avoid duplication of equipment, the system may be connected to the main calibrating circuit of the Hydraulic Machinery Laboratory (1) and the existing facilities utilized for calibration of the three venturi meters. Fig. 2 shows the two points of interconnection.

The main units, i.e., the supply pump, piping, valves, dynamometers, venturi meters, etc. are arranged in a space roughly 19 x 20 feet with above and below floor limitations of 8 and 4 feet respectively. Although the supply pump and reservoir assembly exceed this latter limit inasmuch as it extends down to the sub-basement level, it is so located in the northwest corner of the building as not to interfere with any other laboratory activities. The supply pump motor is visible in Fig. 1.

Briefly, the apparatus covers the following range:

(1) Flow rates up to 4 c.f.s. with a corresponding head differential of 66 feet at the test unit.

(2) Power input or absorption up to 30 hp.

(3) Dynamometers capable of rotative speeds of 100-2000 rpm. in either direction.

The physical size of the test elements is not rigidly fixed. However, rotating channels up to 12 in. diameter and diffuster or volute casings up to 30 in. diameter may be accommodated easily.

Supply Pump and Reservoir

The water supply is furnished by a single-stage, deep-well turbine pump rated at 2.2 c.f.s., 58 ft. head at 1750 r.p.m. By increasing the speed, the pump will deliver up to 4.0 c.f.s. with some reduction of head. The unit is suspended in a casing 20 in. diameter and 24 ft. deep which acts as a combination pump support and reservoir. This construction shown in Figs. 2 and 3, makes possible a unit which occupies little floor area and thus permits its advantageous location in the laboratory. The reservoir may be operated at various water levels and ambient pressures. It also acts as a stilling tank as it allows the separation of air entrained in the fluid returning from the test unit. Mounted integrally with the casing is a 30 hp. dc vertical motor which drives the supply pump. This motor is powered by a 25 k.w. thyraton rectifier equipped to furnish separate field and armature supplies, each of variable output. This system affords stepless speed variation over the entire operating range of the pump. The power supply may be seen along the east wall in Fig. 1.

The supply pump motor speed is held precisely at any set value in order that flow rate and pressure fluxuations resulting from rotative instability be eliminated. The necessary regulation is achieved by an automatic field current control device. The speed control system, shown in Figs. 6 and 7, consists of a mechanical differential one side of which is driven by a synchrorepeater, at the speed of the pump motor. The other side is driven by a synchronous motor supplied from the laboratory constant frequency source (1) operating through an infinitely variable speed transmission. When the speeds of the pump and transmission are matched the differential output shaft is stationary. However, when these two input speeds are mismatched the resultant differential motion rotates a phase shifter which controls the output of the rectifier supplying the field current to the pump motor. The process continues until the pump speed exactly matches the set transmission speed, after which the pump speed remains constant. With this control, it is possible to hold the pump motor exactly at any desired speed between 100 and 2000 rpm.

Venturi Meters and Throttle Valve

For measuring flow rates a bank of three venturi meters is installed downstream from the supply pump discharge. The capacities of these meters are 0.1 to 0.3, 0.3 to 1.0, 1.0 to 3.0 c.f.s. The three are arranged so that by manipulating plug valves, they may be operated singly or in any parallel combination. In this way maximum accuracy of all flow rate determinations is assured. The meters incorporate several unusual design features. First, the approach nozzle contour is calculated to give a continuously decreasing pressure along the nozzle contour and a uniform velocity across the throat section. This type of design eliminates cavitation and separation and insures a consistent venturi calibration independent of system pressure. The method of calculating this type of nozzle, which is used for water or wind tunnel, contraction cones is well known (18). Second, the piezometer openings are made in the form of annular slots (ratio) of width to depth = 1/10) which lead to toroidal collecting chambers within the nozzle flanges. It can be seen in Fig. 8 that the "collector rings" are shaped to permit thorough air venting at the top of the passage when the meter is in its normal, horizontal operating position. Pressure connections are then made at the bottom of these rings.

The flow rates through the meters are indicated by three well-type differential mercury manometers which are equipped with one standard black and white scale, and one machine-engraved brass scale. The latter is fitted with a quick-acting vernier making possible readings to 0.01 inches of mercury. The scales are raised to the centerline of the tubes to minimize parallax when recording data photographically. The maximum deflection per tube is 48 inches. The manometers are shown in Fig. 13.

To assist in obtaining the desired flow rates at the test unit, a throttle valve is installed following the venturi meters. To minimize large-scale flow disturbances and to permit stable control, a special valve was designed, utilizing skin friction as the principal means of head dissipation. As shown in Fig. 9, it consists essentially of a long parabolic plug which travels axially in a matching casing. A lead screw driven through a pair of bevel gears from a handwheel at the test floor level above, positions the plug. This plug is approximately 30 in. long and has an axial movement of 9 in. An indicator gives the axial clearance between the plug and the casing to 0.01 inches, and thus makes it possible to record and duplicate accurately any valve setting. The plug and body contours are so designed that for any opening the flow velocity is nearly constant throughout the throttling section.

Circuit Headers, Valves, Elbows and Couplings

The two 20-inch circuit headers serve primarily as the central distribution and return points for flow to and from the test basins. Their use greatly simplified the laboratory piping and provided the required flexibility. Any entrained air that separates out in these headers is removed by an auxiliary vacuum line which is provided on the top of each.

To accomplish the numerous circuit changes required by the various test set-ups, eight 10-inch valves are installed between the headers and the test section. These valves are operated either fully open or completely closed. Preliminary consideration led to the design and manufacture of a very simple and light line-blind type valve for this service. The valve is shown in Fig. 10 in partially-open, open, and closed positions. It consists essentially of two companion flanges and a brass plate which separates the flanges and is free to rotate between them. As shown in the illustration this plate can be positioned to give either an unobstructed opening or an absolute closure. By swinging the four dogs into position and clamping up, the plate is tightly sealed against "O" rings set in the flange faces. It weighs 25 pounds assembled, occupies 4 1/4" of axial distance, and requires 12 inches head room to swing the rotating plate.

To reduce serious circuit disturbances arising from the several short radius turns, vane-elbows are used. Fig. 11 shows the construction of a finished elbow. To facilitate changes, connections are made with "Victaulic" couplings.

Test Sections

The various flow paths to and from the test sections are shown in Fig. 2. To smooth the flow when approaching the test unit in an axial direction, as in the case of a normal pump impeller or reverse turbine runner studies, a honeycomb is installed in the vertical approach line. It is located approximately four diameters from the base of the approach nozzle and built up from 1/2-inch square brass tubing 5 inches long, so assembled as to give a minimum blocking.

A transparent lucite nozzle reduces the approach pipe diameter to the impeller or runner eye diameter and allows visual and photographic observations in this region. The elevation of the nozzle may be varied approximately six inches. A nozzle and impeller are shown in position in Fig. 1.

Since pump impellers discharging freely into the atmosphere are at present under consideration, a light metal cylinder 32 inches high and 30 inches in diameter is sealed to the test stand bedplate and serves adequately to collect the impeller discharge. It may be used for either right or left hand channel rotation by merely connecting the return line to the appropriate outlet nipple, Fig. 4. As testing progresses, continued revisions of this unit are anticipated. Thus, the present simple expendable design is most desirable. Attention is called to the large, unobstructed area immediately about the test unit which allows considerable latitude for test basin modification.

Dynamometers

The two dynamometers as shown in Figs. 1 and 4, are vertically mounted direct-current motors cradled in brackets which are rigidly fastened to opposite sides of a large box column of welded construction. The column base carries the test section bed plate and the approach piping. This construction makes the entire test section from dynamometer to approach an integral balanced unit, the rigidity of which is independent of the supporting structure. These features make it possible to align accurately the rotating channel with the approach nozzle and to maintain a close-running clearance between the two. Each dynamomemter is mounted in its bracket on ball bearings to permit the frame to rotate in response to shaft torque. The bearing loads are extremely small compared to their rated capacities, and for this reason it was considered unnecessary to rotate the races to prevent brinnelling. Adequate working space above the rotating channel was obtained by extending the dynamometer drive shaft approximately two feet below the bracket base.

A torque arm extends from the frame of the dynamometer and bears against a preloaded metallic bellows that is part of a completely filled fluid system. The system pressure, a linear function of the shaft torque, is indicated by a precision pressure gage. A volume compensator is incorporated in the pressure line to limit the torque arm motion at the bellows to ($\pm$) .005 in. In this way the effects of temperature changes in the closed system and volume changes inherent in the pressure gage are eliminated and the restoring forces of the dynamometer wiring and bellows on the torque measurements are minimized.

Thrust measurement requires an axially-free impeller drive with a force-measuring device to restrain its motion. That this might be done easily, the shaft extension was separated from the armature shaft by a thrust-free coupling, Fig. 12. A hole bored through the motor shaft permits a 1/2-inch "thrust-shaft" to connect rigidly the impeller or runner to the thrust-measuring device on top of the dynamometer bracket. This device will consist of a bellows and a hydraulic circuit similar to that used for torque measurement.

Since the dynamometers will never be operated simultaneously, they share one 25 kw, 250 V., d.C. power supply which, with the exception of dissipating resistors for power absorption, is identical in construction to the one used for the service pump.

Precise speed control of the dynamometers is essential for the maintenance of steady flow conditions. Here again an automatic field-regulatory device is used. Except for the type of variable speed transmission, it is practically identical with supply pump control. In this unit the transmission consists of a series of gear trains so arranged as to allow dynamometer speed changes in increments of 1 rpm. This feature makes it possible not only to hold constant the dynamometer speed, but also to know the exact magnitude of that speed. The device controls speeds between 100 and 2000 rpm. This selective gear box, together with the associated electrical control circuits is a direct development from the speed control system in use for many years in the Hydraulic Machinery Laboratory (1).

On top of the dynamometer and driven by it, are the speed control selsyn transmitter and an electric tachometer generator. Both are mounted on the dynamometer frame to prevent their driving torques from affecting the torque measurements.

Instrumentation

The principal quantities required for the determination of the operating characteristics of a rotating channel are speed, torque, rate of flow, and inlet and outlet pressures. The provisions made for measuring torque, speed and flow rate have been discussed. For all negative pressures and for positive pressures up to 20 psi mercury manometers of the same construction as previously described, are used. Higher pressures are indicated by precision, bourdon-type pressure gages. Fig. 13 shows the arrangement of the gage panel. For total head determination of a rotating channel with a free discharge, cylindrical, three-hole pitot tubes and a sensitive no-flow pressure gage are available. To assist in making velocity distribution studies about the discharge of rotating channels, a pitot tube which rotates with the channel is under consideration.

The desirability of using photographic methods in flow studies has been mentioned. Their use, however, requires that the test passages be transparent and that suitable photographically identifiable particles or tracers be present in the stream. A technique is being developed whereby transparent rotating channels may be manufactured with a high degree of accuracy and reproducibility in the laboratory. In the interim, a medium specific speed cast aluminum closed impeller with front and back shrouds replaced with ones of lucite is under preliminary observation. A simple and satisfactory tracer material has been found to be a mixture of carbon tetrachloride and benzene proportioned to give a sp.gr. of 1.0. This mixture is immiscible with water and when injected into the flow forms globules which retain their identity, and, when properly illuminated, are photographically discernible.

Of the various photographic techniques available (12,17), several of particular interest are now either in use or under consideration. The simplest employs a single camera with a fixed film or plate upon which a series of exposures are made by a controlled burst of flashes of a high speed multiflash lamp. When the flash rate is properly matched to the channel rotative speed, the familiar golf-ball type pictures shown in Fig. 16 results. In this manner, a number of positions of the tracer at various known time intervals may be recorded and the magnitude and direction of the tracer's velocity in the plane of the plate are calculable. This method, while satisfactory for two-dimensional flow observation is inadequate for a complete study of the three-dimensional picture and hence its use in these investigations is correspondingly limited. This limitation is overcome by viewing the channel stereoscopically. Either two cameras or one camera equipped with a beam splitter may be used and simultaneous exposures made in exactly the same manner as before. From a stereoscopic analysis of the data, the complete trajectory of the fluid particle is obtainable.

With a fixed film, tracers in areas immediately adjacent to the vanes are often partially, if not totally, obscured as may be seen in Fig. 16. To overcome this difficulty, high speed motion pictures are to be employed wherein a single exposure is made at each flash. Again, single or stereoscopic pictures may be taken and by appropriate analysis, the flow pattern may be determined.

V. Preliminary Experiments

The present preliminary rotating channel has been used primarily in developmental studies of experimental techniques. Although this work has been principally visual in nature, a number of interesting photographic records have been obtained. Five of these photographs are presented in Figs. 14 through 18 inclusive. With the exception of Fig. 18, they are photographs of the same impeller when operating as a normal pump under identical conditions, i.e., $N = 240$ rpm, $H = 2$ ft., $Q = 0.75$ c.f.s. Fig. 14 is a multiflash picture of the impeller with carbon tetrachloride-benzene tracers in the passages. The images of these tracers (retouched for reproduction purposes) illustrate one of the techniques useful in determining the velocity field. Fig. 15 is the result of a relatively long time exposure and shows the absolute velocity pattern of the flow at discharge, whereas Fig. 16 is a high speed single flash exposure and reveals the relative velocity pattern. Rather striking in this picture are the surfaces of discontinuity which originate at the vane tips. The preceding photographs are taken with the water level in the test basin at the elevation of the impeller top shroud. When this level is lowered, the flow discontinuities, evident in Fig. 16, build up in the time of discharge descent and form the "steps" or "terraces" seen in Fig. 17. When a centrifugal pump impeller is rotated in a direction opposite to that of normal, the impeller will operate in the abnormal pumping regime (15). Fig. 18 shows the relative flow pattern at discharge under this condition of reverse rotation where N = 100, Q = 0.46 c.f.s., H = 1 ft.

It is clear from the foregoing discussion that the fundamental interest of the laboratory is in the basic research of hydraulic machine components. With the use of the existing facilities of the Hydrodynamics Laboratory, i.e., the instrument shop, electronics laboratory, and photographic laboratory, it is hoped that the problems described in the introduction will come within experimental grasp, and followed by analytical investigations be gradually clarified.

BIBLIOGRAPHY

1. Knapp, R. T., "The Hydraulic Machinery Laboratory at the California Institute of Technology", Trans. A.S.M.E., Paper HYD-58-5, vol. 58, Nov., 1936, pp. 649-661.

2. Knapp, R. T., Levy, Joseph, O'Neill, J.P., and Brown, F. B. "The Hydrodynamics Laboratory of the California Institute of Technology", Trans. A.S.M.E., Vol. 70 No. 5, July, 1948, pp. 437-457.

3. Oertli, H., "Untersuchung der Wasserstromung durch rotierendes Zellenkreiselrad," Rascher and Cie, Zurich, 1923.

4. Barth, W., "Verdrängungsströmungen bei Rotation Zylindrischer Schaufeln in einer Flüssigkeit mit freier Oberfläche," Mitteilungen des Instituts fur Strömungsmaschinen der Technischen Hochschule Karlsruhe, No. 1, 1930, p. 39.

5. Closterhalfen, A., "Hilfsmittel zur Beobachtung und Messung an umlaufenden Kreiselrädern," Forschung auf dem Gebiete des Ingenieurwesens, vol. 2, No. 1, 1931, p. 2 and No. 2, p. 52.

6. Closterhalfen, A., "Versuche an einer Schaukreiselpumpe," Forschung auf dem Gebiete des Ingenieurwesens, vol. 2, July, 1931, p. 252.

7. Fischer, K. and Thoma, D., "Investigation of the Flow Conditions in a Centrifugal Pump," Trans. A.S.M.E., vol. 54, 1932, paper HYD-54-8, p. 141.

8. Stiess, W., "Über die Relativ-Strömung in einen Pumpen-Laufrad von grossem Radien-Verhältnis," Mitteilungen des Instituts für Strömungsmaschinen der Technischen Hochschule Karlsruhe, No. 3, 1933, p. 77.

9. Hagmayer, E., "Messungen des Druckverlaufes uber Lauf und Leitschaufel einer Kreiselpumpe," Ph.D. thesis, Technische Hochschule Braunschweig, 1932.

10. Frietsch, "Wirbelbildung und Kräftewirkung an umlaufenden Kreiselschaufeln, " V. D. I. Forchungsheft 384, 1937.

11. Hahn, K., "Die Untersuchung der Strömung durch eine Flügelradturbine bei verschiedenen Schaufelzahlen, Mitteilungen des Instituts fur Strömungsmaschinen der Technischen Hochschule Karlsruhe, No. 4, 1939, p. 2.

12. Knapp, R. T. and Hollander, A., "Laboratory Investigations of the Mechanism of Cavitation", Trans. A.S.M.E., Vol. 70, No. 5, July 1948, pp. 419-435.

13. Knapp, R. T., "Centrifugal-Pump Performance as Affected by Design Features", Trans. A.S.M.E., April, 1941, pp. 251-261.

14. Binder, R. C., and Knapp, R. T., "Experimental Determinations of the Flow Characteristics in the Volutes of Centrifugal Pumps", Trans. A.S.M.E., vol. 58, Nov., 1936, pp. 649-661.

15. Knapp, R. T., "Complete Characteristics of Centrifugal Pumps and Their Use in the Prediction of Transient Behavior", Trans. A.S.M.E., Paper HYD-59-11, Nov., 1937, pp. 683-689.

16. Peabody, R. M., "Pump Discharge Valves on the Colorado River Aqueduct", Trans. A.S.M.E., Presented at Semi-Annual meeting of A.S.M.E., July, 1939.

17. Knapp, R. T., "Special Cameras and Flash Lamps for High-Speed Underwater Photography", Jour. Soc. Mot. Pic. Eng., vol. 49, no. 1, July, 1947, pp. 64-82.

18. Tsien, Hsue-Shen, "On the Design of the Contraction Cone for a Wind Tunnel", Jour. Aero. Sci., vol. 10, no. 2, Feb. 1943, pp. 68-70.

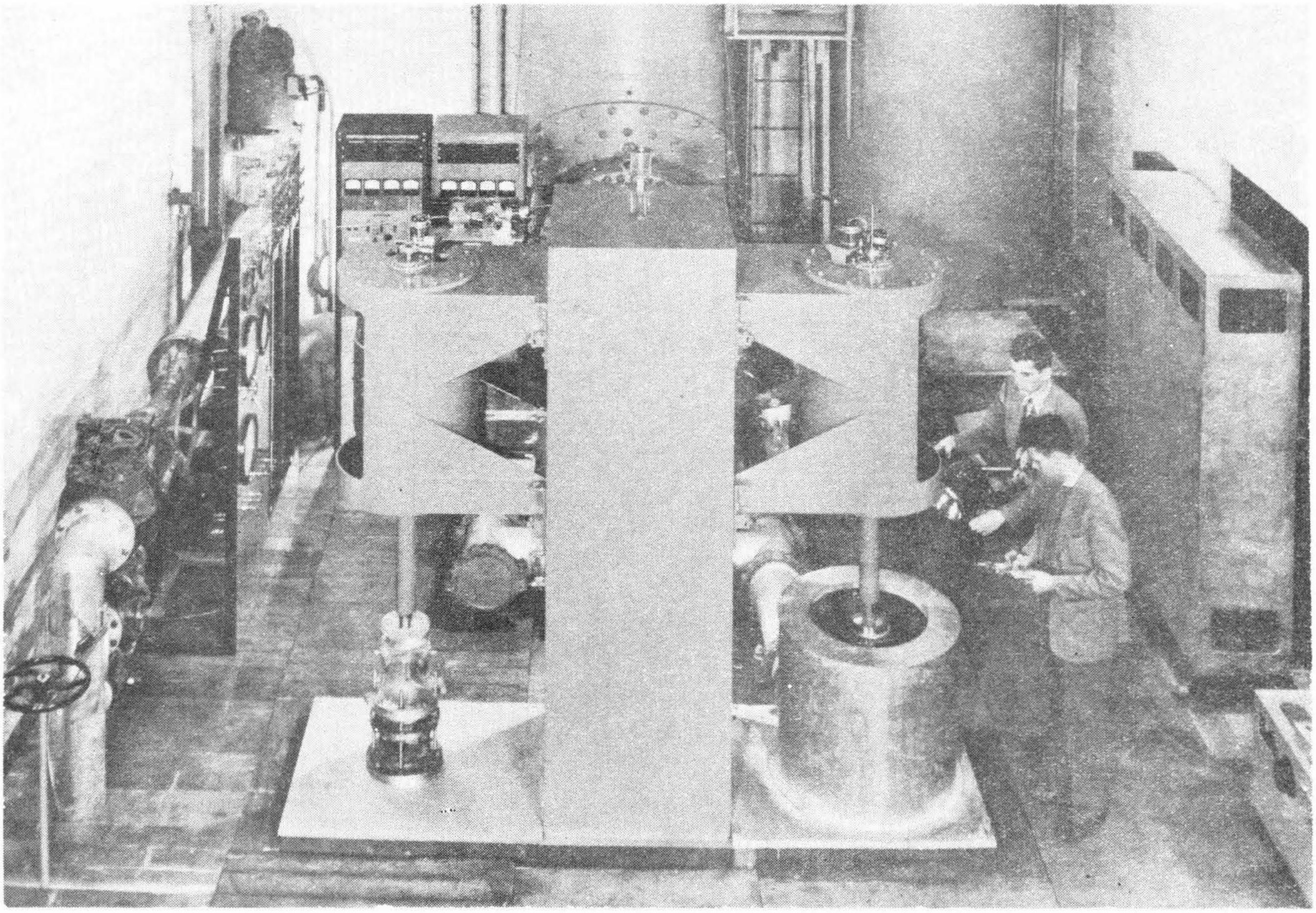

FIG. 1 — VIEW OF ROTATING CHANNEL PROJECT LOOKING NORTH, SHOWING TEST STAND IN FOREGROUND. TEST BASIN ON LEFT HAS BEEN REMOVED TO SHOW APPROACH CONSTRUCTION

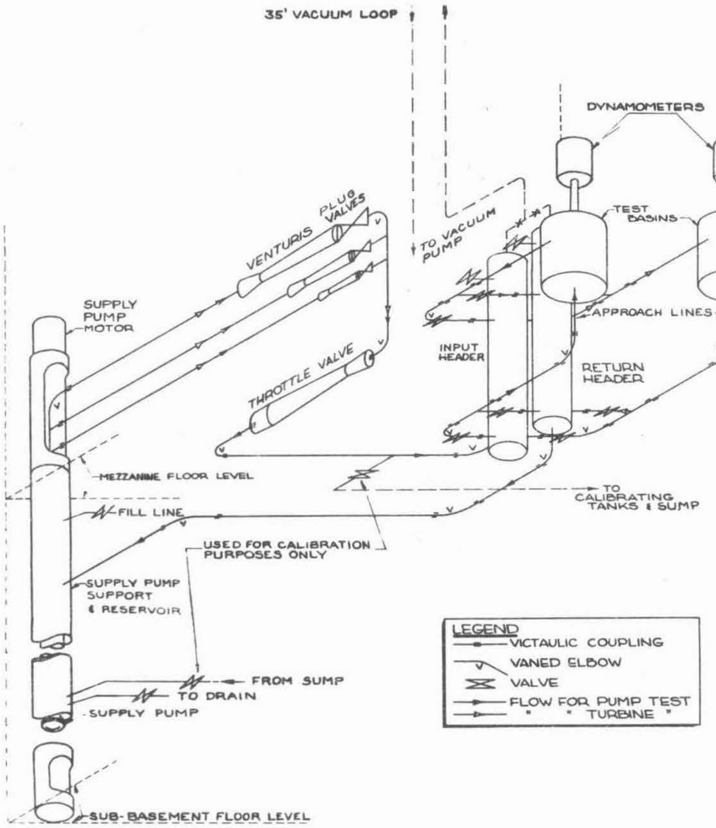

FIG. 2 – SCHEMATIC DIAGRAM OF MAIN AND AUXILIARY FLOW CIRCUITS

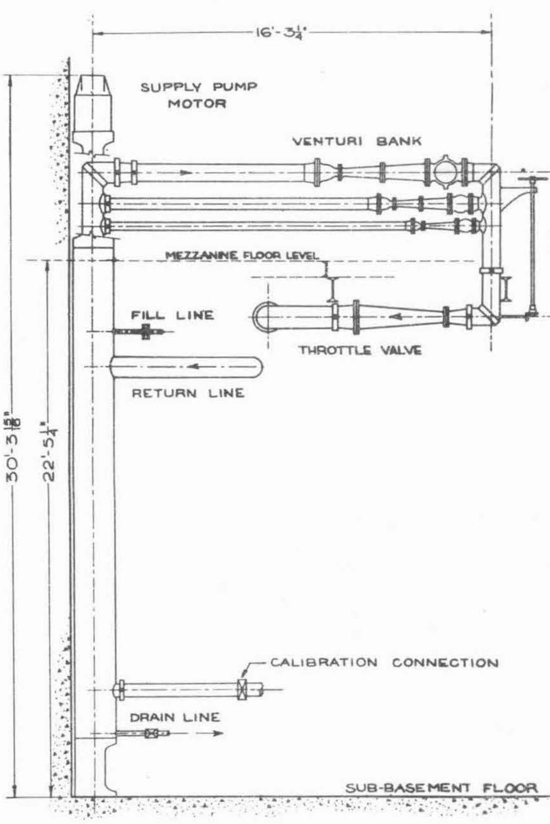

FIG. 3 – VIEW OF CIRCUIT LOOKING EAST SHOWING SUPPLY PUMP AND RESERVOIR, VENTURI METERS AND THROTTLE VALVE

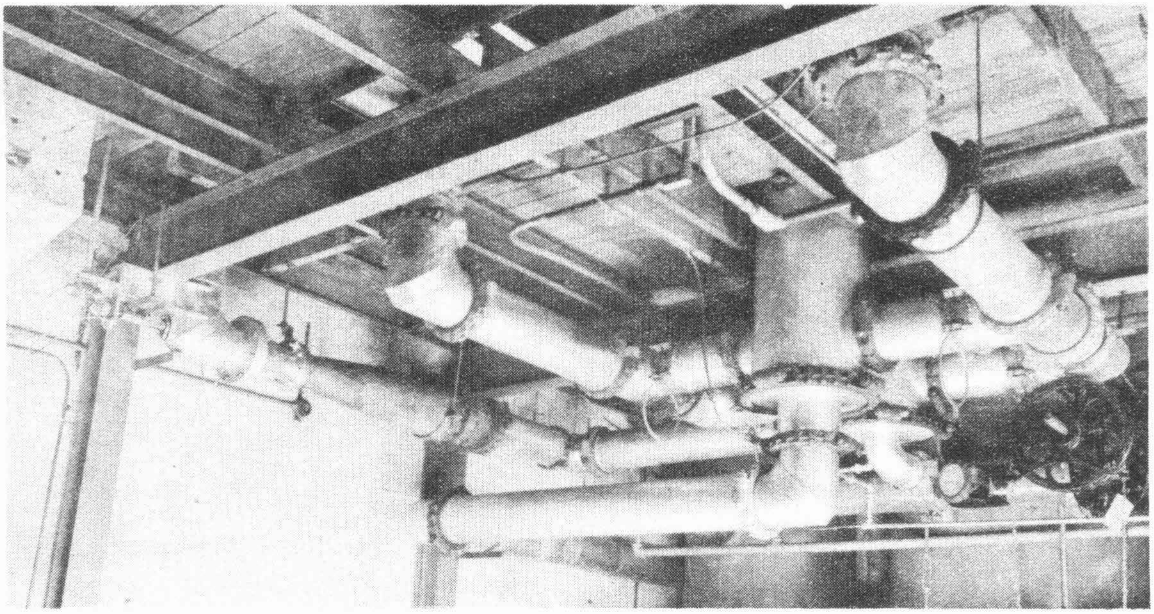

FIG. 4 — CIRCUIT PIPING BELOW OPERATING FLOOR, LOOKING NORTH. THE TWO VERTICAL APPROACH LINES APPEAR IN FOREGROUND

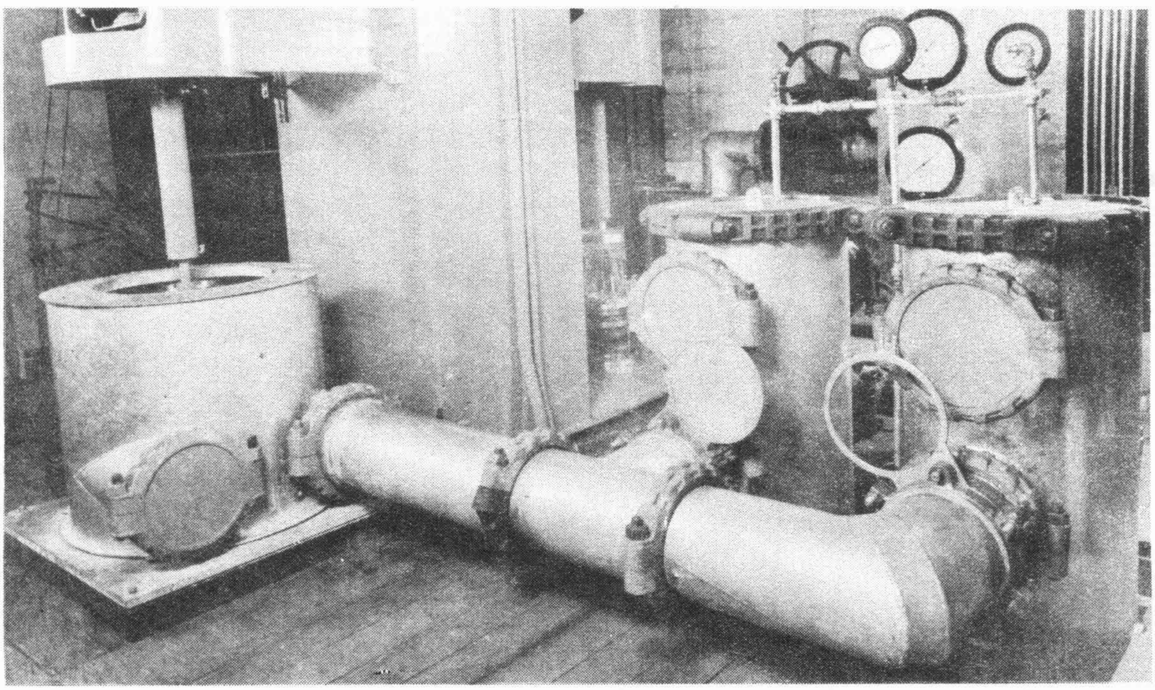

FIG. 5 — VIEW OF TEST STAND LOOKING SOUTH SHOWING DISTRIBUTING HEADERS AND FITTINGS IN FOREGROUND

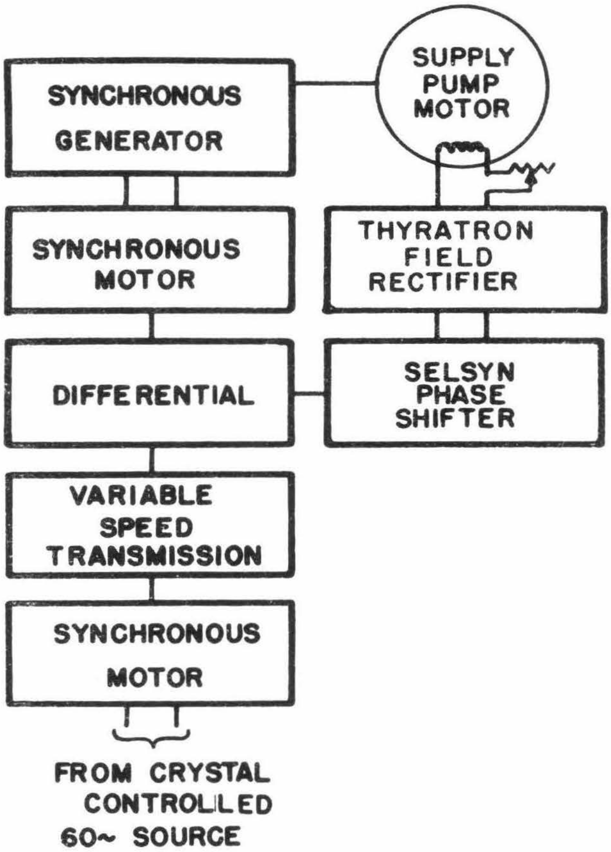

FIG. 6 — BLOCK DIAGRAM OF SUPPLY PUMP MOTOR SPEED CONTROL

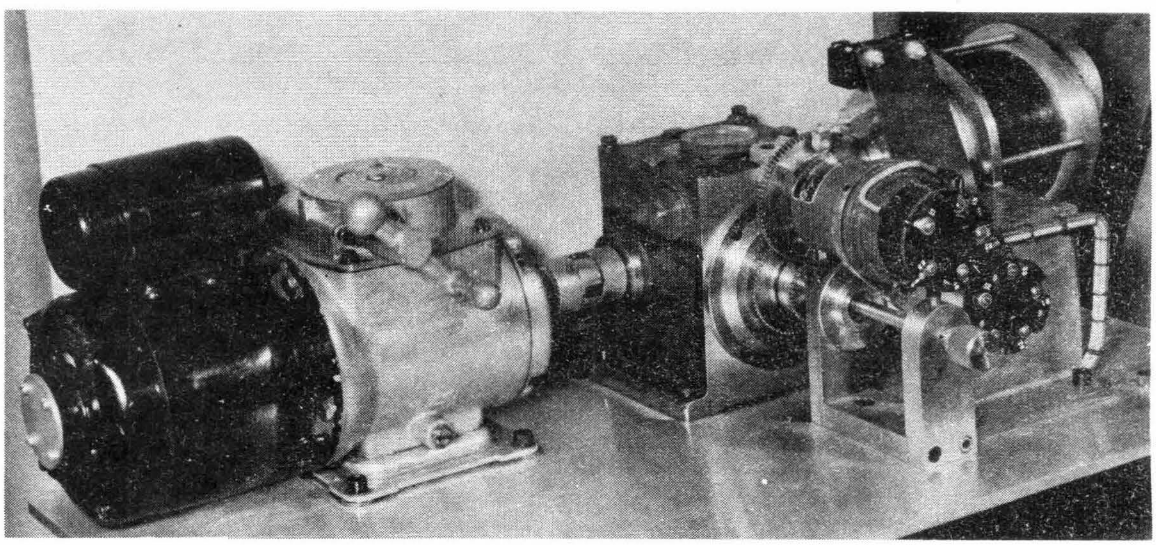

FIG. 7 — SUPPLY PUMP MOTOR SPEED CONTROL

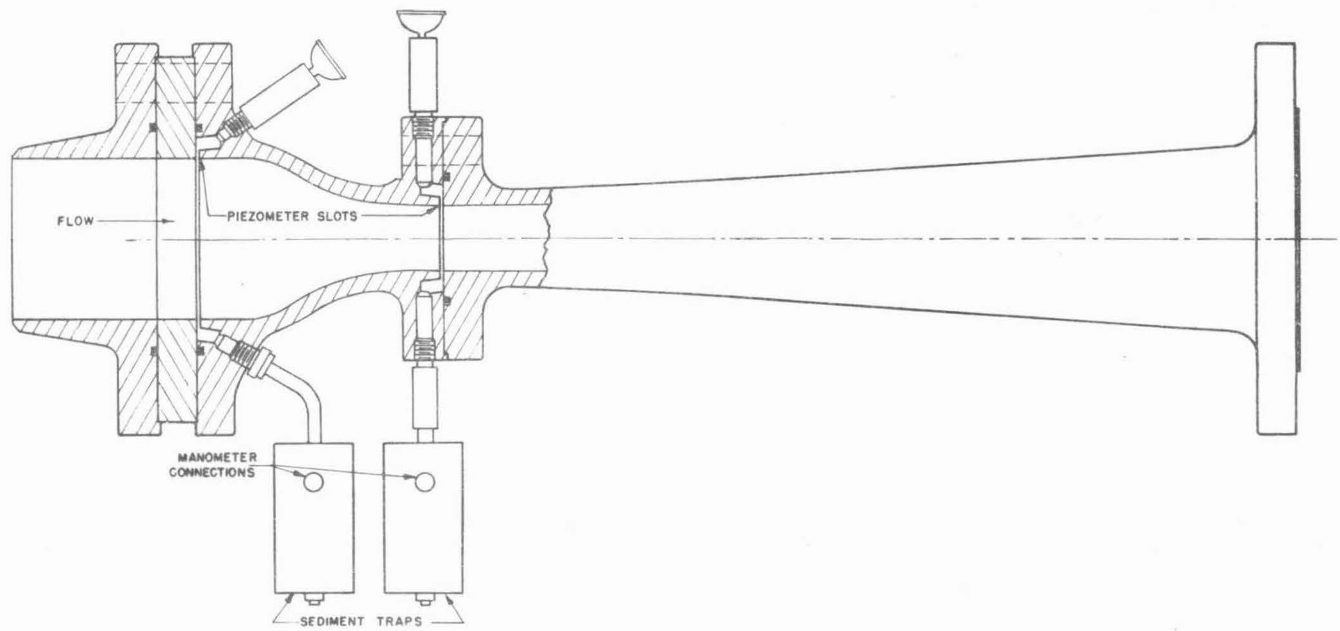

FIG. 8 — CROSS SECTION OF A VENTURI METER

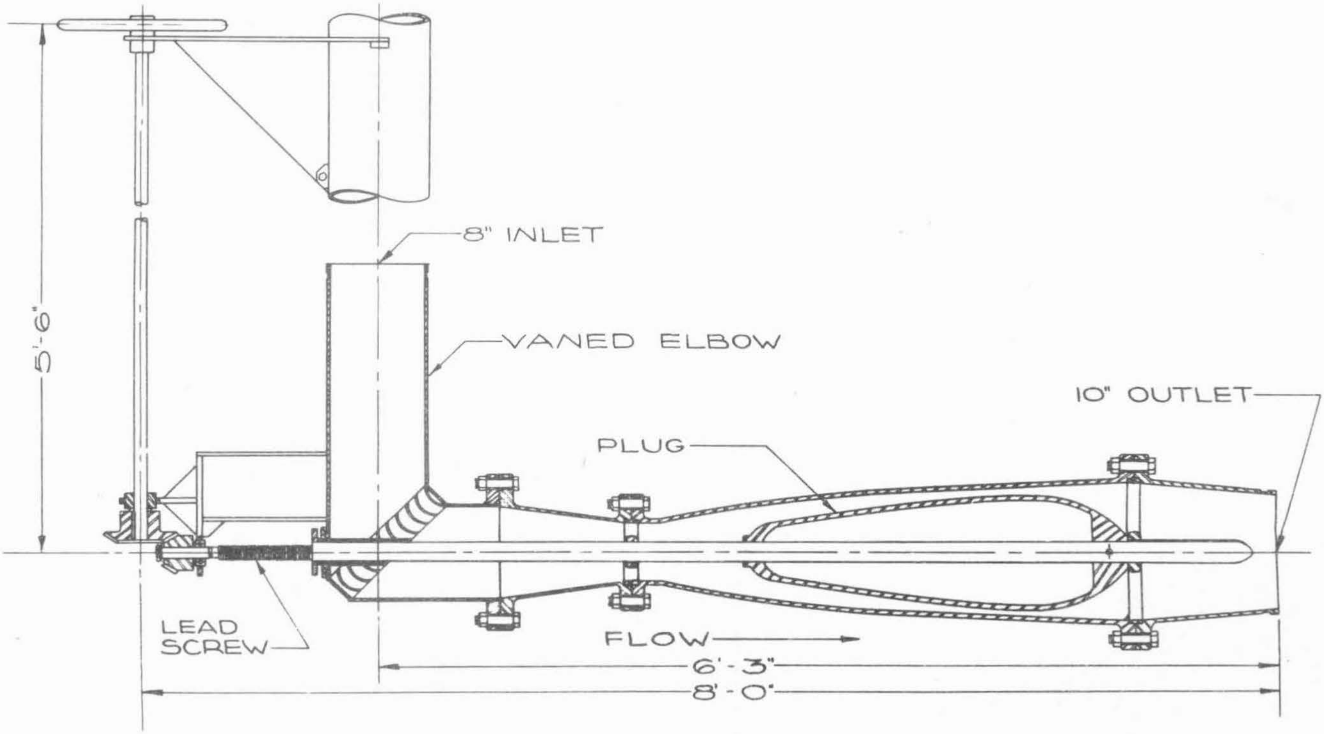

FIG. 9 — CROSS SECTION OF THROTTLE VALVE

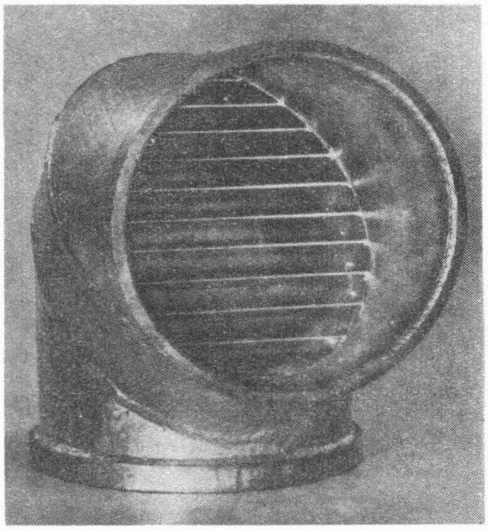

FIG. 10 – A FABRICATED 10 IN. GALVANIZED VANE ELBOW

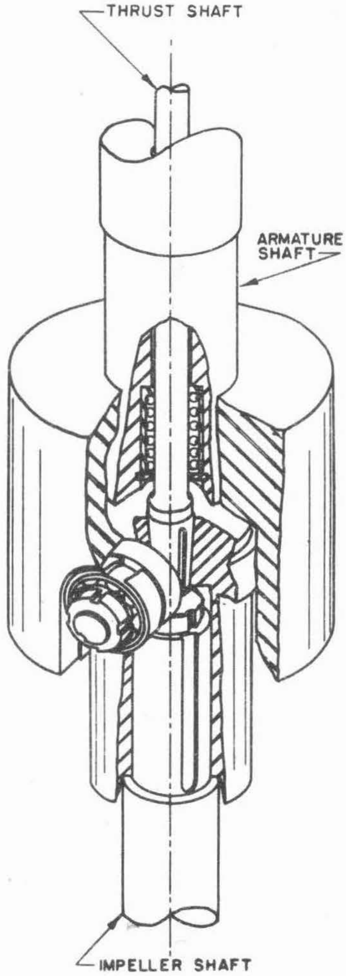

FIG. 12 – DYNAMOMETER THRUST-FREE COUPLING

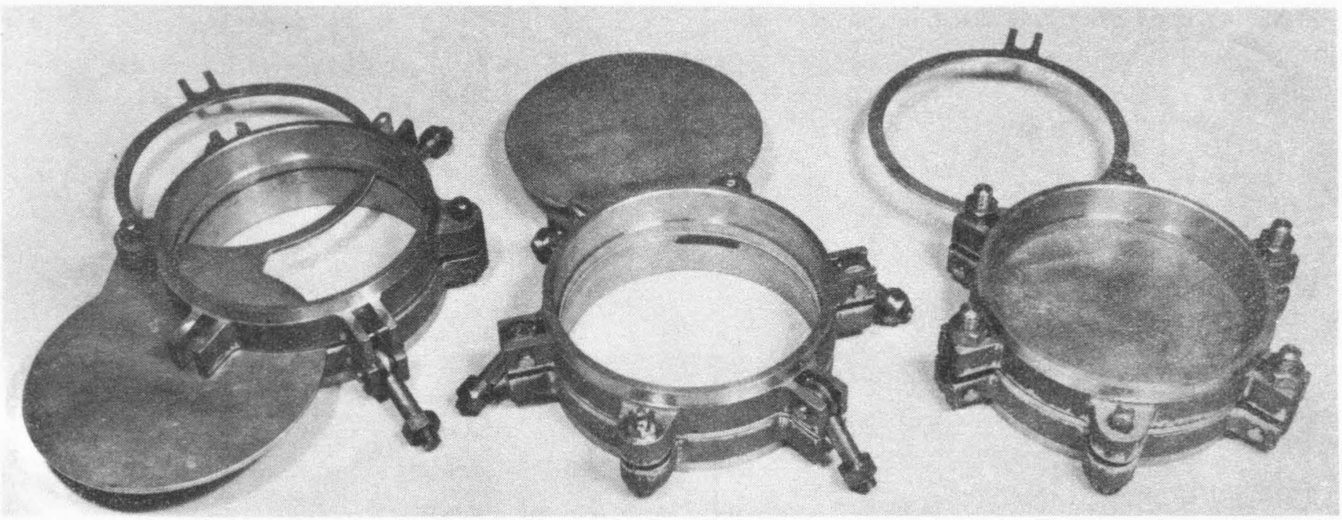

FIG. 11 – LINE BLIND VALVE SHOWN IN PARTIALLY OPEN, OPEN, AND CLOSED POSITIONS. THE VALVE IS USED EITHER FULLY OPEN OR COMPLETELY CLOSED

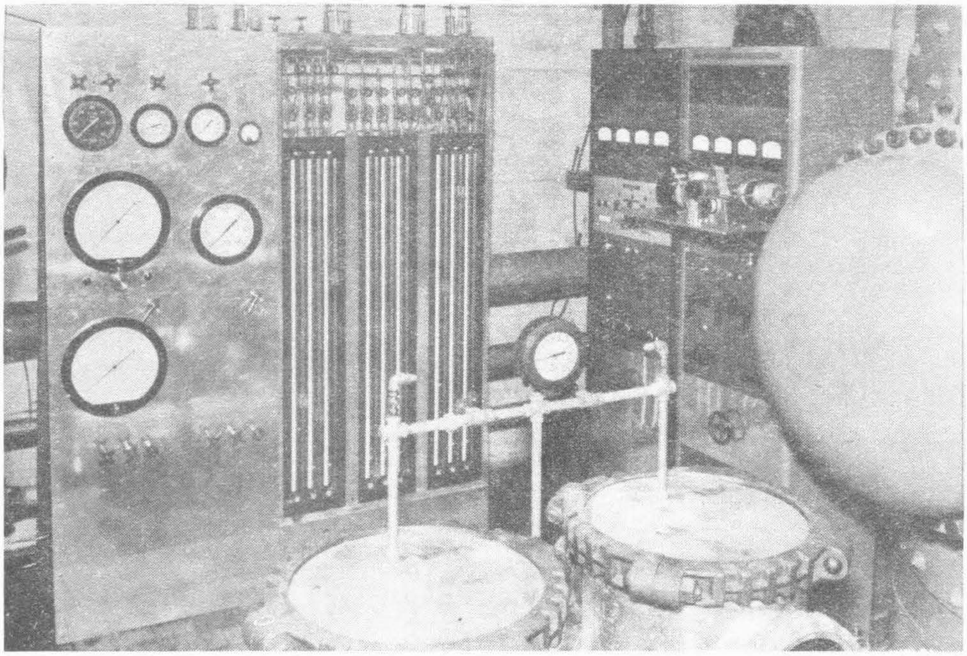

FIG. 13 – GAGE RACK SHOWING MERCURY MANOMETERS AND PRESSURE GAGES. TO THE RIGHT OF THE GAGE RACK CAN BE SEEN THE ELECTRICAL CONTROL PANELS FOR THE DYNAMOMETERS AND SERVICE PUMP MOTOR

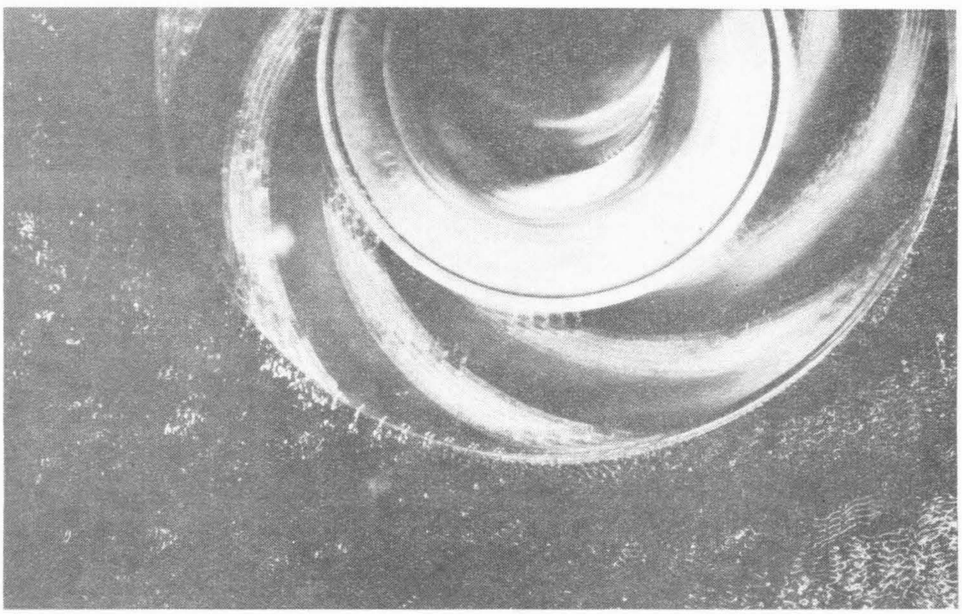

FIG. 14 – MULTIFLASH PHOTOGRAPH OF IMPELLER WITH CARBON TETRACHLORIDE–BENZENE GLOBULES IN THE PASSAGES

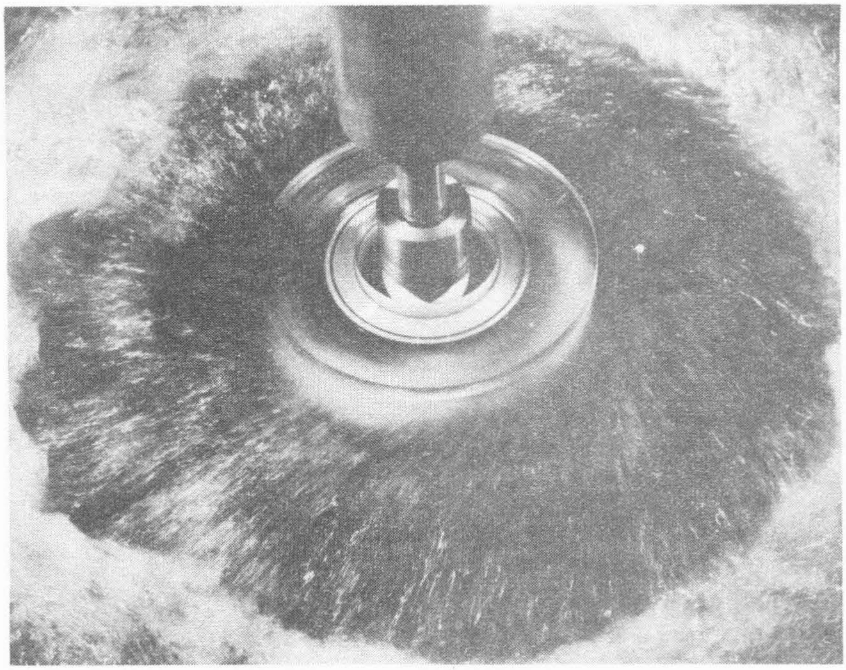

FIG. 15 — LONG—EXPOSURE PHOTOGRAPH OF DISCHARGE FROM A HIGH EFFICIENCY CENTRIFUGAL PUMP IMPELLER WITH BACKWARD CURVED VANES ROTATING IN A CLOCK—WISE (NORMAL) DIRECTION. NOTE DIRECTION OF FLOW IN THE ABSOLUTE VELOCITY PATTERN. WATER LEVEL IN TEST BASIN IS AT THE TOP SHROUD OF IMPELLER.

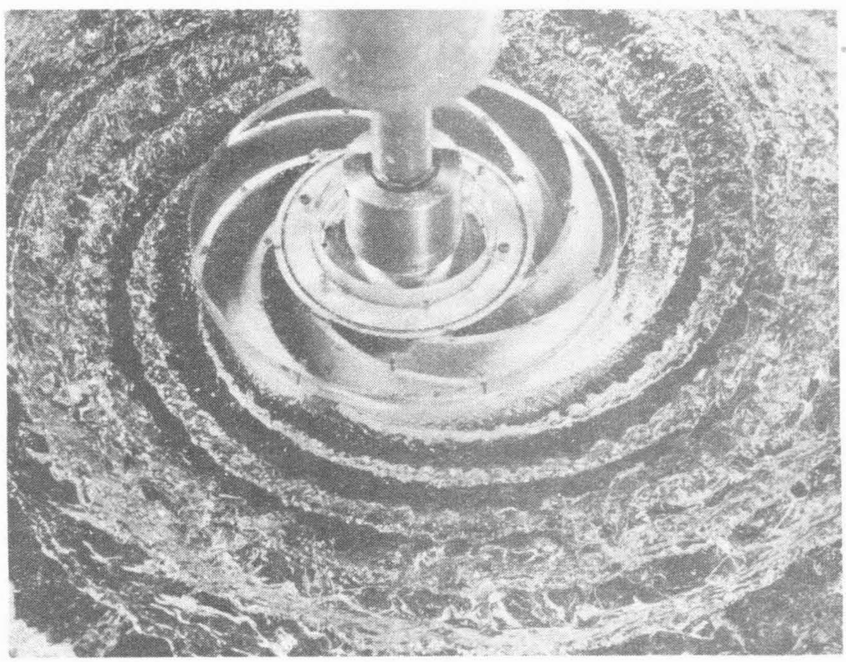

FIG. 16 — INSTANTANEOUS PHOTOGRAPH OF FLOW SHOWN IN FIG. 15 SHOWING THE GENERAL CHARACTER OF THE RELATIVE FLOW PATTERN

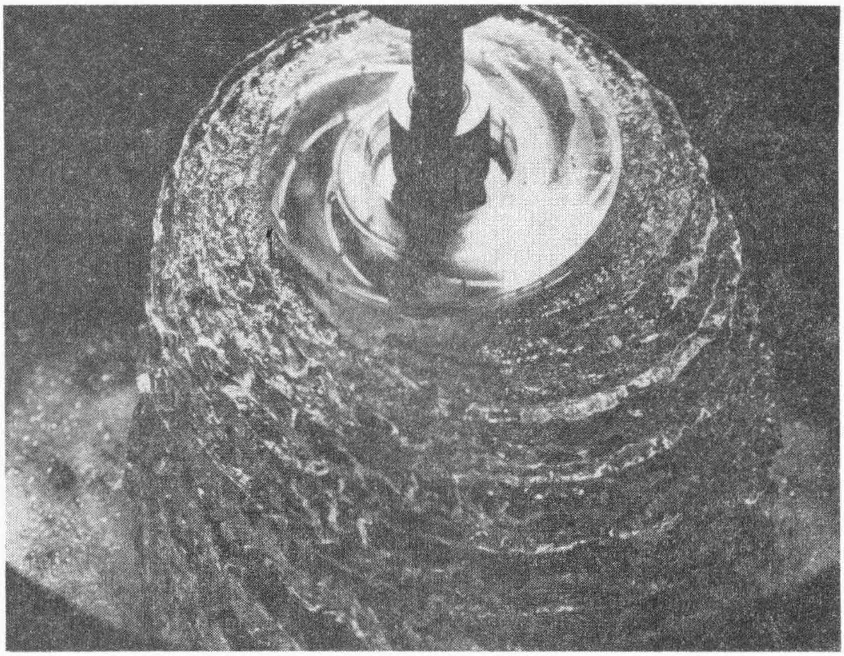

FIG. 17 — INSTANTANEOUS PHOTOGRAPH OF THE IMPELLER DISCHARGE WITH THE TEST BASIN WATER LEVEL LOWERED. TIME SPENT IN DESCENT BY THE FREE DISCHARGE ALLOWS DISCONTINUITIES IN THE RELATIVE VELOCITY PATTERN TO BUILD UP UNTIL DEFINITE "STEPS" ARE VISIBLE

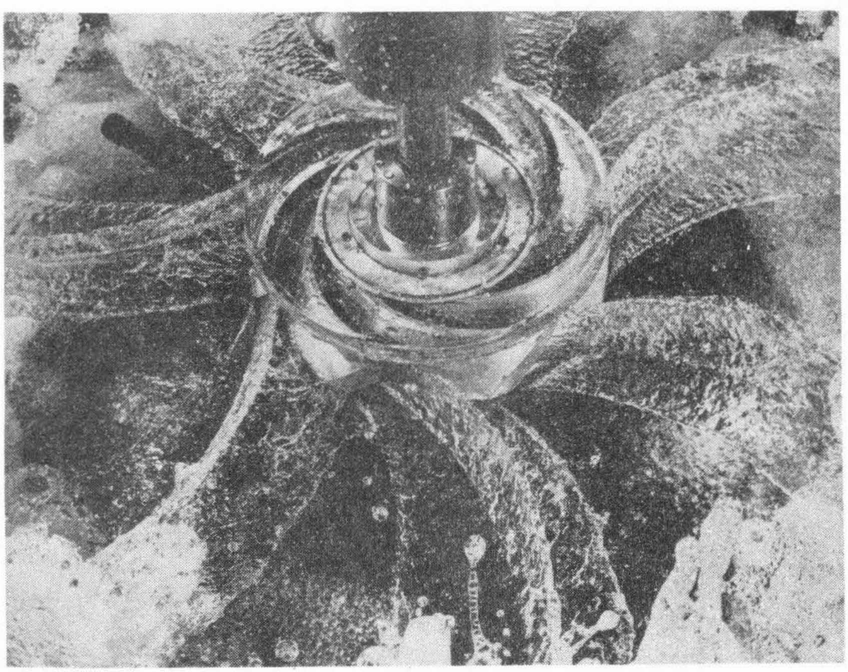

FIG. 18 — INSTANTANEOUS PHOTOGRAPH OF THE FLOW FROM AN IMPELLER ROTATING IN A COUNTER-CLOCKWISE (REVERSE OF NORMAL) DIRECTION